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Comparative Analysis between PI and Fuzzy Controllers for Dc Voltage Control of Unbalanced 4 Wire Shunt Active Power Filter

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Abstract-This research proposes a shunt active power filter (SAPF) for harmonics mitigation in order to improve power quality of the electrical network. The reference harmonic current extraction technique used was based on DQ0 power theory under unbalanced non-linear loads conditions for four wire-installed systems. The DC-link voltage plays an important role in SAPF design to guarantee both steady high voltage level for harmonics current chopping and support the inverter power losses. In order to maintain constant DC link voltage, two different controllers are used; PI controller and fuzzy logic controller. A comparative analysis has done between the two controllers. Hysteresis PWM has used for current conditioning.

Keywords- Power quality, Harmonics current, Shunt active power filter, DQ0 extraction technique, PI controller, Fuzzy logic controller, Hysteresis PWM-unbalanced loads.

I. Introduction

"Power Quality" is defined as "Set of parameters defining the properties of power quality as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude and waveform) in IEC. This means that a perfect power supply would be one that is always available, always within voltage and frequency tolerances and has a pure noise- free sinusoidal wave shape. Just how much deviation from perfection can be tolerated depends on the user's application, the type of equipment installed and his view of his requirements. IEEE defined power quality disturbances into seven categories based on wave shape: [1-5].

1. Transients
2. Waveform distortion
3. Interruptions
4. Voltage fluctuations
5. Sag / Under voltage
6. Frequency variations
7. Swell / Overvoltage

This has leaded to the proposal of more stringent requirements regarding power quality and standards such IEEE-519, which reflects these preoccupations. IEEE Std.1159-1995, recommended Practice for Monitoring Electric Power Quality. This standard covers recommended methods of measuring power quality events as shown in Figure1.

Wave distortion is the most important problem in power quality as it is a steady state deviation from an ideal sine wave. The most general type of wave distortion is harmonics. In recent years, with the rapid development of the power electronic technology, various power electronic devices and nonlinear elements, especially of many kinds of rectifier and switcher, are applied widely in power system.

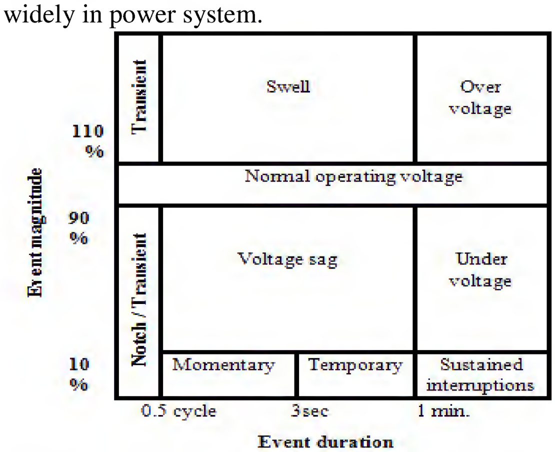

Figure 1. Definitions of Events by IEEE Std.1159.

Harmonics have produced serious adverse effects in the equipment of power generators and distribution system, and of their control and protection, as well as the users and the communication fields[6]. There are many problems caused by harmonic currents such as overloading of neutrals, Overheating of transformers, Skin effect and higher Losses[7]. The total harmonic distortion (THD) of currents and voltages is shown in equation (1) and (2).

$$\text{For voltage: } THD_v = 100\left(\frac{\sqrt{V_h^2}}{V_1}\right) \quad (1)$$

$$\text{For current: } THD_i = 100\left(\frac{\sqrt{I_h^2}}{I_1}\right) \quad (2)$$

Where; I_h,V_h are currents and voltages of a certain harmonic order.There are two types of harmonics matigation methods. The first one is passive filters. Its disadvantages is that the source impedance, which is not accurately known and varies with the system configuration, strongly influences filtering characteristics of the shunt passive filter [8].The filter may be overloaded when the harmonic current components increase. At a specific frequency an anti resonance or parallel resonance occurs between the source impedance and the shunt passive filter [9]. As the load changes, a passive filter may need to be disconnected, converted or replaced by new one[10]. The second

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harmonic mitigation method is shunt active power filter (SAPF).To compensate the distorted currents,SAPF injects currents equal but opposite to the harmonic components, thus only the fundamental components flow in the point of common coupling (PCC). Four wire SAPF is connected in parallel to the loads, unbalanced and non-linear loads as shown in Figure2,which causes the supply currents to be completely sinusoidal and balanced [11-12].

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \\ I_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ -\cos\theta & -\cos\left(\theta - \frac{2\pi}{3}\right) & -\cos\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{3}$$

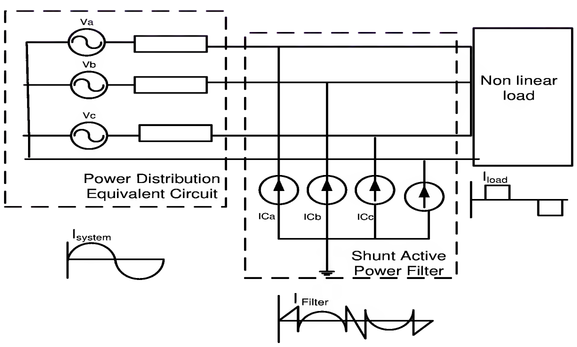

Figure 2. Basic shunt active power filter compensating system.

II. Reference current extraction technique based on (DQ0)

The performance of this filter depends on three parts:

1. Reference current extraction circuit and control technique.
2. PWM inverter technique
3. The control of D.C capacitor voltage and the circuit responsible on this control.

Reference current extraction technique is the heart of the SAPF design. it is implemented in three stages. There are many techniques used to extract the compensating command of the harmonic signal. These techniques are based on frequency domain, time domain and artificial intelligence. This paper concerns in DQ0 extraction technique in time domain.

In this method, the load current is converted into the rotating frame using (Park transformation) in the presence of zero sequence current due to the current passing in the neutral as in equation (3). To transfer from ABC frame to DQ0 rotating frame, phase lock loop (PLL) is required to generate theta, sine and cosine signals needed to be synchronized with the various phase to neutral voltages as shown in Figure3.

With a simple high-pass filter, the DC part can be easily removed from i_{Lde} and i_{Lqe} and the remaining can be transformed into its previous frequency with a reverse transformation. The oscillating parts of i_{Lde} and i_{Lqe} represents the harmonic content of the load current as in equation (4) .

$$\begin{aligned} i_{Lde} &= \bar{i}_{Lde} + \tilde{i}_{Lde} \\ i_{Lqe} &= \bar{i}_{Lqe} + \tilde{i}_{Lqe} \end{aligned} \tag{4}$$

The two oscillating parts of the load current in the rotating frame represents the reference current of the active filter. Then it is transformed to the ABC frame as in equation (5).

$$\begin{bmatrix} I_{Ca}^{*} \\ I_{Cb}^{*} \\ I_{Cc}^{*} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta & -\cos\theta & \frac{1}{\sqrt{2}} \\ \sin\left(\theta - \frac{2\pi}{3}\right) & -\cos\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ \sin\left(\theta + \frac{2\pi}{3}\right) & -\cos\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} \tilde{i}_{Lde} \\ \tilde{i}_{Lqe} \\ I_0 \end{bmatrix} \tag{5}$$

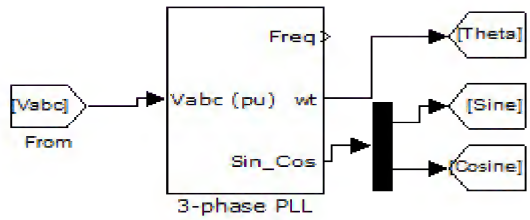

Figure3. Theta generation using PLL.

III. DC-link voltage control

Voltage control require feedback control loop that is responsible to keep its voltage stable at the reference value with minimum error. The actual DC voltage VDC_{act} is compared with a reference VDC_{ref} (the reference voltage the capacitor must be charged to). The error signal obtained from this comparison is used to control the voltage. The amplitude of the current that is required from the system to charge the capacitor when its voltage decreases than the reference voltage ($\Delta \mathbf{I_{dc}}$) is evaluated using equation (6):

$$\Delta I_{dc} = G_c * e = G_c(VDC_{ref} - VDC_{act.}) \tag{6}$$

Where; G_c represents a *PI* or *fuzzy* gain. This current will form a part of the reference current that the inverter must follow in case of harmonic compensation

In this paper, two controllers are used in maintaining constant DC link.

IV. PI controller

The term tuning is used to describe the process of selecting the optimum controller setting in order to obtain the best performance from PI controller. The most widely used methods are Ziegler and Nichols. They assumed one procedure called ultimate cycle method which is based on using results from a closed- loop test. With a control system employing a PI controller, K_P, K_I have to be selected. Such selection determines the response of the control system to the inputs [11]. PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller.

The difference between the actual and set reference DC voltage,which is the error, is passed through a PI controlller which converts this difference into the required charging current ΔI_{dc} to the capacitor to compansate the inverter losses as shown in In Figure4. the reference DC voltage is choosen 600V to be larger than the highest V_{line} in the system. ΔI_{dc} is considered a

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peak value of the supply current, which is composed of two components:
1. Fundamental active power component of load current.
2. Loss component of SAPF, to maintain the average capacitor voltage to a constant value.

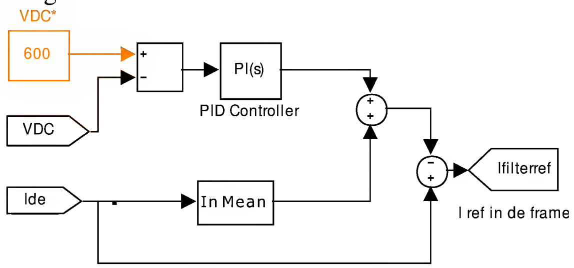

Figure4. Idc control using PI controller.

V. Fuzzy logic controller

The advantages of fuzzy controllers over conventional controllers are that they do not require an accurate mathematical model, can work with imprecise inputs and more robust. The Mamdani type is used. The fuzzy controller is based on two inputs; error and its derivative and one output, which are the command signal to fuzzy controller.

Figure5 shows the internal structure of the control circuit. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to the zero steady error in tracking the reference voltage signal.

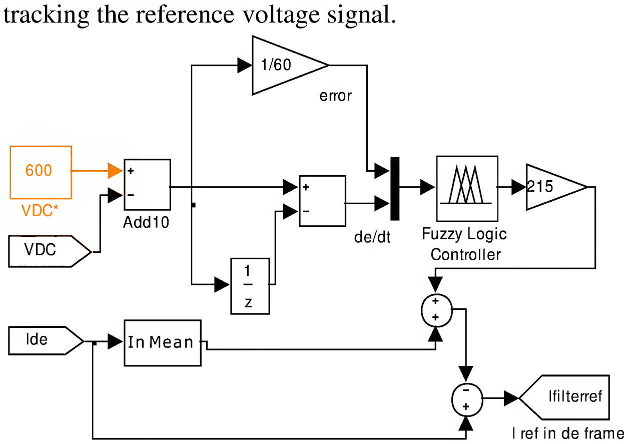

Figure5. Idc control using Fuzzy Logic controller.

Design of control rules:

The fuzzy control rule design involves defining rules that relate the input variables to the output model properties. As fuzzy logic controller is independent of system model, the design is mainly based on the intuitive feeling for, and experience of the process. The rules are expressed in English like language with syntax such as If {error E is X and change of error ΔE is Y} then {control output is Z}. For better control performance finer fuzzy petitioned subspaces {big negative, negative, zero, positive, and big positive} are used and summarized in Table 1. The two inputs, error and change in error, are three memberships; negative, zero and positive and characterized using Gaussian membership. Five membership functions are for output and characterized using triangular and trapezoidal membership functions [13]-[15]. These memberships are shown in Fig 6(a) and 6(b).

Error / de/dt	Negative	Zero	Positive
Negative	Big positive	Positive	Big Positive
Zero	Big negative	Zero	Big Positive
Positive	Big neagtive	Negative	Big Positive

Table 1. Fuzzy controller Rule Base

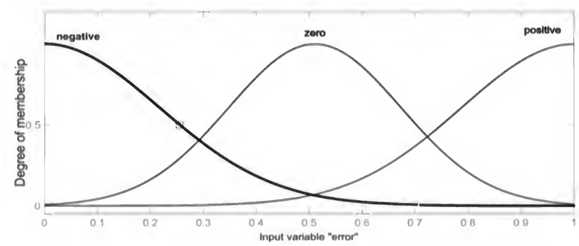

Figure 6(a). Input Variable Error 'E' and dE Gaussian M.F.

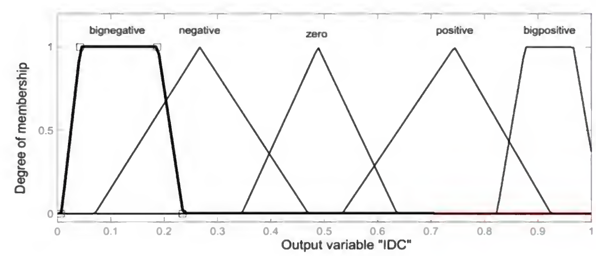

Figure 6(b). Output "ΔId.c" Normalized M.F.

VI. Simulation results of the proposed system

1. PI controller

The simulation tests were obtained by using the computational tool MATLAB/SIMULINK to verify the proposed system as shown in Figure7. The system parametes are shown in Table 2. The simulated system is consists of an A.C source,SAPF and unbalanced load. This load is consists of three single phase diode recifier with differnent connected loads. The SAPF is connected to the system through an inductor. The source currents of phases A,B,C and neutarl currents before compansation are shown in Figure8,9,10 and 11. It is clear that the unbalaned loads caused a high current zero sequence current value passing through the neutral wire.The three source currents are highly distorted. Different connected loads to the phases causes unbalnance between them as shown in Figure12

Source voltage V_s	220V, 50Hz.
Source inductance L_s	1.5mH
Source resistance R_s	0.6Ω
Active filter inductance L_{sh}	2 mH
DC side voltage reference	600V
Active filer DC side capacitance	1500μF
Hystresis band	0.001

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Unbalance load:	
Load1: Single phase diode bridge rectifier with parallel RC load	R=50 Ω, C=800μF
Load2: Single phase diode bridge rectifier with parallel R load	R=15 Ω
Load3:Single phase diode bridge rectifier with series RL load	R=15 Ω, L=0.1H

Table 2. The studied system parameters

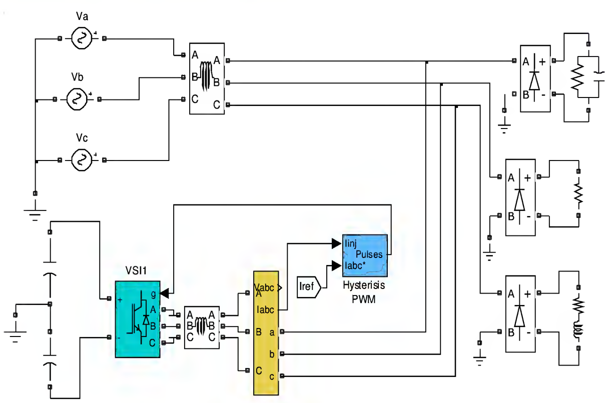

Figure7. Overall proposed simulated system.

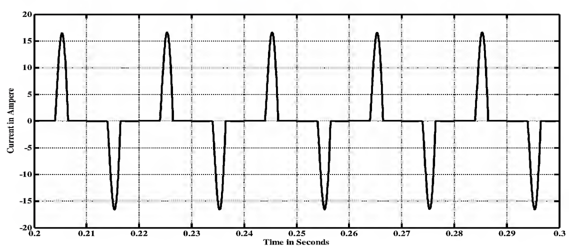

Figure8. Source current of phase A before compansation.

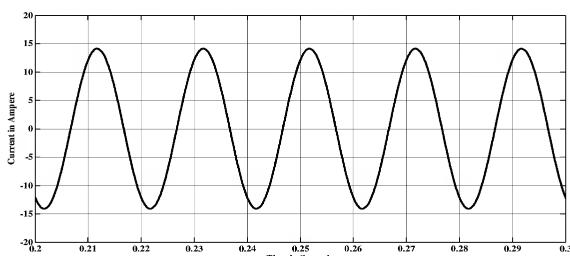

Figure9. Source current of phase B before compansation.

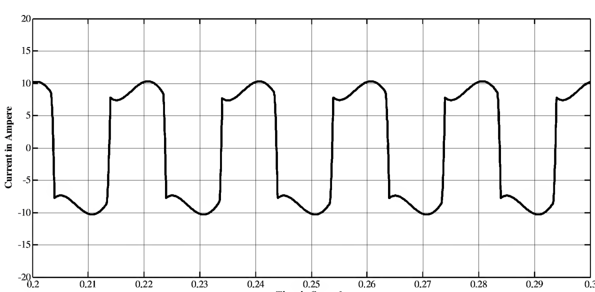

Figure10. Source current of phase C before compansation.

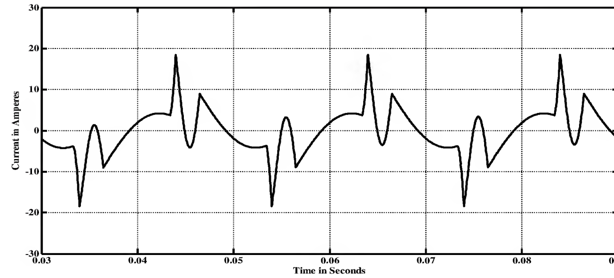

Figure11. Neutral current before compansation.

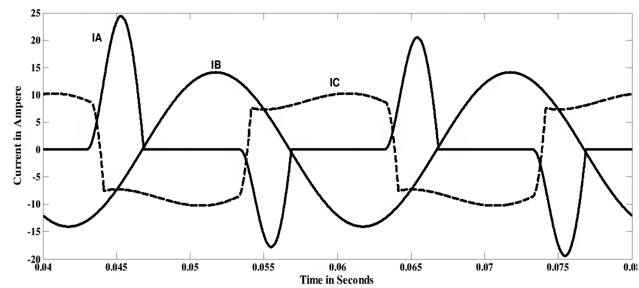

Figure12. Unbalanced source currents.

The compansated currents of the shunt active power filter in each phase are shown in Figure 13,14 and15. These current will be injected to the system at PCC to reshape the source current to pure sine wave. Notice that the compansating current of phase B is sinusodal wave and this is excepected due to its resestive load. This compansating current will be added to the source current of phase B in order to maintain balance between all the source currents. The performance of the hysteresis controller appears in the above compensating current curves. The controller successes in tracking the calculated reference filter current. The proposed system makes an excellent mitiagtion in the current harmoinc in the source current. The source and neutral currents after compansation is shown in figures 16,17,18 and 19.

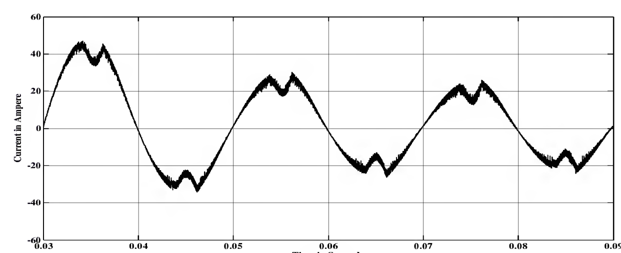

Figure13. Compansating current of phase A.

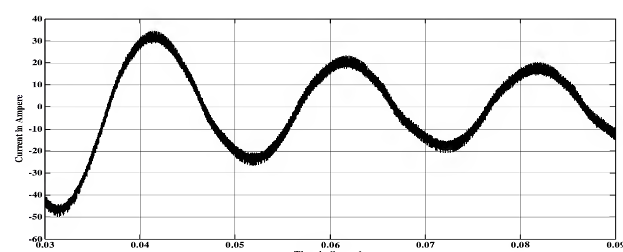

Figure14. Compansating current of phase B.

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It is clear that the proposed SAPF succeeded in mainating balance between different phases as shown in Figure 20. The steady state current value is the same in phase A,B and C and equals to 30 Ampere. The current in the neutral is decreased to a very low value nearly equals to 4 ampere.

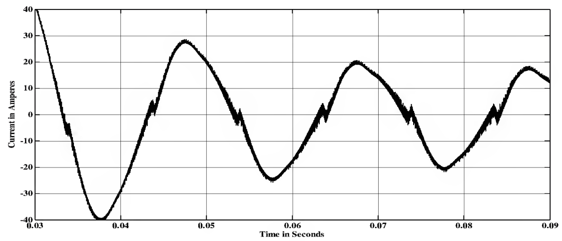

Figure15. Compansating current of phase C.

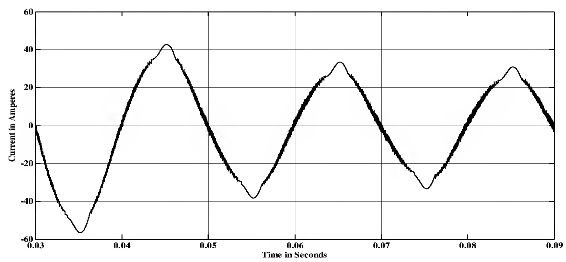

Figure16. Source current of phase A after compansation.

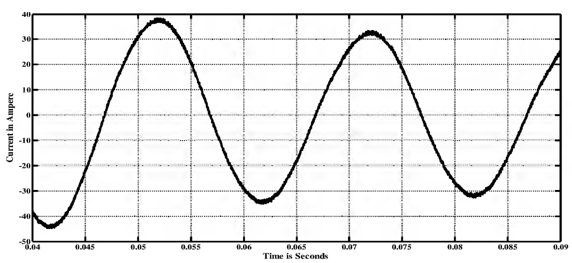

Figure17. Source current of phase B after compansation.

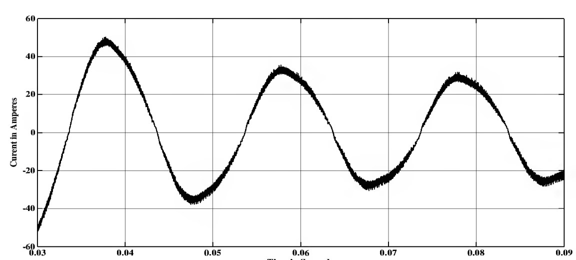

Figure18. Source current of phase C after compansation.

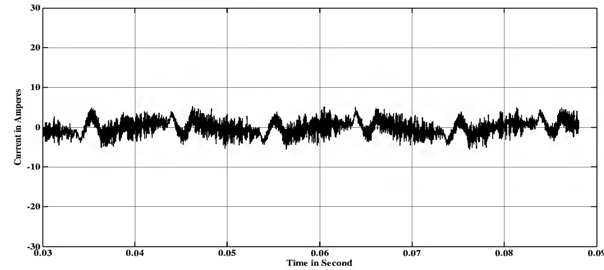

Figure19. Neutral current after compansation.

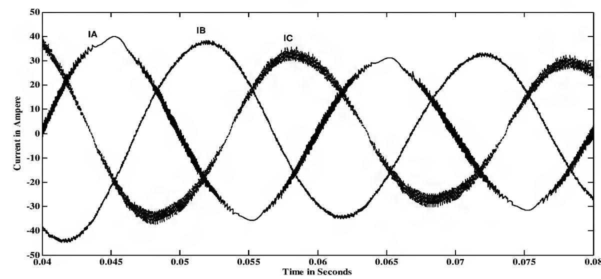

Figure20. Balanced source currents .

Table 3 summarized the THD of the source currents before and after compensation. It can be seen in figure 21 that the PI controller has an very good performance in maintaing the reference value. It takes nearly three complete cycles to reach the steady state reference value (600V). This reflects that the P (proportional) value is better chosen. At 0.09 second the steady state error is very small and this reflects that the I (integral) value is perfect. The value of the **K_P=0.6, K_I=3.5**. The tuning of these values is using Ziegler and Nichols [11].

	THD before SAPF	THD after SAPF
Phase A	125.05%	5.864 %
Phase B	Linear load not affected by SAPF	
Phase C	37.76%	7.358%

Table 3. The THD of phases using PI controller

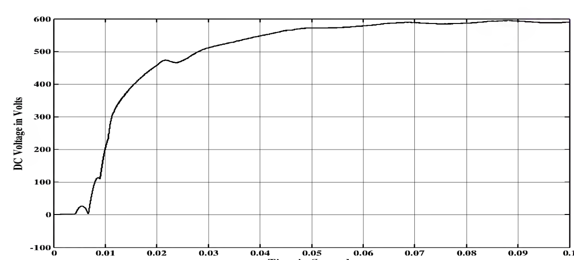

Figure21. Voltage of the PI DC link.

2. Fuzzy logic controller

The simulation was repeated using fuzzy to study the effect of changing the DC controller on maintaing the DC reference value.The controller scucced in tracking the reference signal and compensating current tracks the reference calculated one. We foucued on the DC voltage curve shown in Figure22 and on the THD values of the source currents before and after compansation as shown in Table 4 .

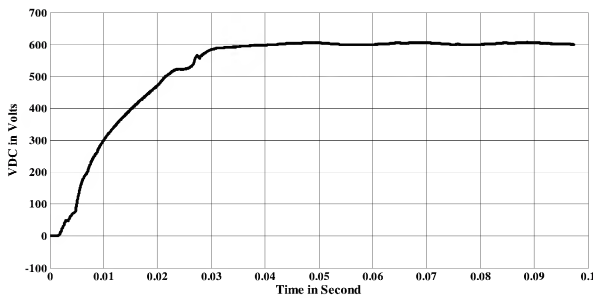

Figure22. Voltage of the fuzzy DC link.

	THD before SAPF	THD after SAPF
Phase A	125.05%	5.118%
Phase B	Linear load not affected by SAPF	
Phase C	37.76%	6.61%

Table 4. The THD of phases using fuzzy controller

It can be seen in Figure 22 that the Fuzzy controller has an excellent performance in maintaing the reference value. It has fast response as it takes only one cycle and half to reach the steady state reference value (600V). After 0.05 second the steady state error is nearly null.

VII. Conclusion

In this paper, four wire SAPF based on DQ0 strategie for reference currents extraction is considered. The three-phase voltage source inverter using Hysteresis PWM succeeded in tracking the three-phase reference currents waveforms. The proposed system had been implemented using MATLAB/Simulink. PI and fuzzy controllers are used for maintaing constant DC voltage under unbalanced load conditions. SAPF using PI controller mitigate harmonics and decreases THD in phases A,C to 5.84% and 7.358%.
Fuzzy controller is used and simulation results demonstrate that even if the supply current is unbalanced , the performance of fuzzy controller showed better compensation capabilities in terms of THD than with PI. THD decreases to 5.118% in phase A and 6.61% in phase B.
SHAF using fuzzy controller has been found to be closer to the IEEE 519–1992 standard recommendations on harmonic levels, making it easily adaptable to more severe constraints. The proposed SAPF using both controllers has compensated the neutral harmonic currents and the DC bus voltage is almost maintained at the reference value under all disturbances, which confims the effectiveness of both controllers.

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